LEARNING 5 EXPERIENCE

LANGUAGE OF THE CELL

PROLOGUE Imagine that you have been asked to redesign your school building. You can rearrange rooms, knock down walls, and build new wings. The first stage in the remodeling process will probably involve drawing up a plan. This plan will guide how each of the new components fits together in the new design plan and, ultimately, how the new structures will work. The plan must be clear and accurate for builders to follow.

Other sorts of plans—the play book for an athletic team, the musical score for a jazz group—work in much the same way. The information stored in the plan is read and translated into action. The information is used to construct a winning play or a resonant blend of instruments.

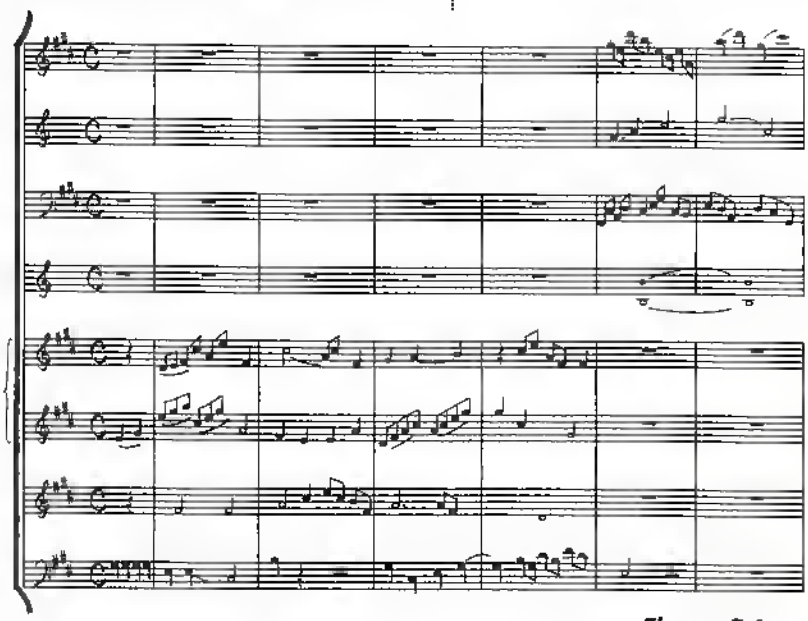


Figure 5.1
Musical score

Avery and Griffith's work suggested that DNA might also be some sort of plan. This plan was thought to carry information that, in some way, could direct the expression of new characteristics or traits, such as a polysaccharide coat on *Diplococcus pneumoniae*. Scientists did not know what this plan looked like or how it might work.

In these situations, when the detailed workings of a biological phenomenon are a mystery, a researcher needs to start thinking creatively about the possibilities. What *could* it look like and how *might* it work? How do other plans work? How do they encode information? How is that information used? In this learning experience, you begin by analyzing how information is deciphered and used in two sorts of plans—a musical score that produces a particular melody, and a blueprint that produces a particular kind of house. These analogies are then applied to understanding DNA as yet another kind of plan.

Figure 5.2a
Cross section through the side of a house, with a list of construction materials

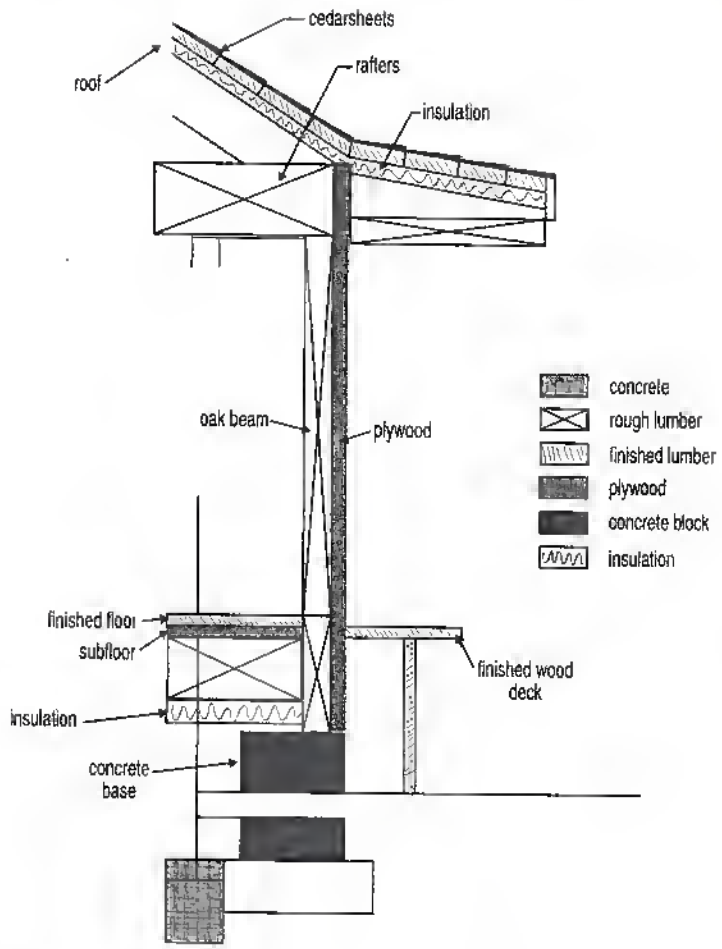
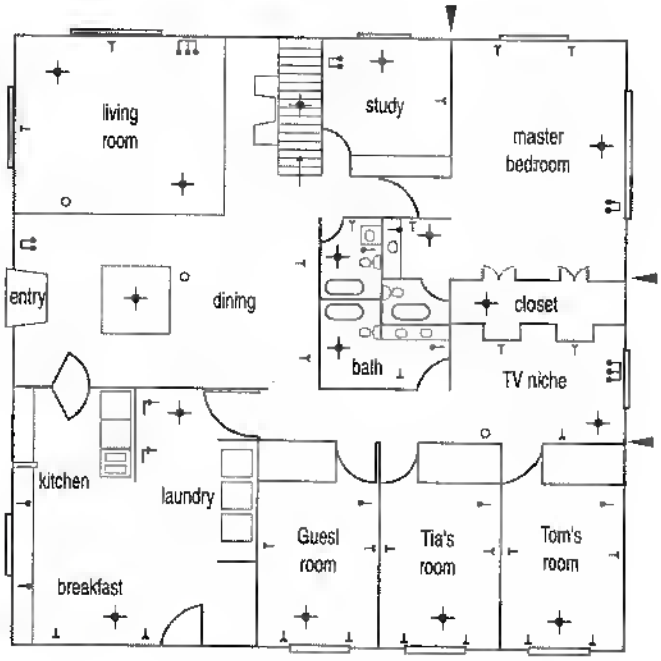


Figure 5.2b
Blueprint of house floor plan, including plans for outlets, and lighting

- Light fixture
- Utility outlet
- Counter height utility outlet
- Floor outlet
- Flood light
- Wall switch
- Two way wall switch
- Three way wall switch



ANALYSIS

1. How do you go about reading music? Deciphering a floor plan? What do the plans mean? What information do you need to know to make sense of them?
2. What information do the symbols tell you about the music? the house?
3. What features remain constant within each plan? Which ones change?
4. How do the symbols relate to one another? How might the order or the placement of the symbols affect the code?
5. What features do the blueprint and the musical score have in common?

ACTIVITY

BUILDING DNA

INTRODUCTION If DNA is responsible for conferring the characteristic of virulence on *D. pneumoniae*, can the next assumption be that DNA codes for all characteristics or traits of an organism? Does DNA itself have the characteristics necessary for such a task? How is it possible for the molecule to carry the information necessary? Researchers recognized that whatever they were looking for must have the capacity to carry an enormous amount of information—all the instructions necessary for determining the biochemical activities and specific characteristics of the cell and the organism.

Two researchers investigating the role of DNA were James Watson and Francis Crick. In 1953, they proposed a model for the structure of DNA which gave some clues as to how it might work within the cell. Their model-building process was one of trial and error, making adjustments as they learned critical pieces of evidence from other researchers. For example, Maurice Wilkins and Rosalind Franklin's work with X-ray crystallography gave important information about the spiral architecture of DNA called the "double helix."

The building blocks of DNA, termed *nucleotides*, are composed of three kinds of molecules: (1) a group of oxygen atoms clustered around a phosphorus atom (known as a *phosphate group*), (2) a simple sugar, attached to a (3) base. The base may be any one of

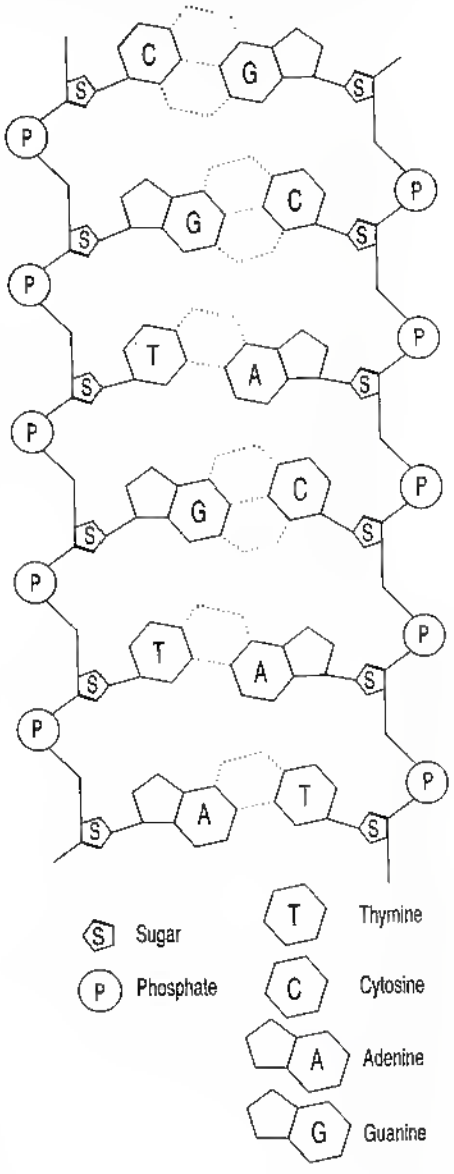


Figure 5.3
Which features remain constant in all DNA molecules? Which differ?

four rather similar nitrogen-containing bases: *adenine* (A), *thymine* (T), *guanine* (G), and *cytosine* (C).

Erwin Chargaff discovered two key "rules" which helped in figuring out how the four nucleotides were put together. Chargaff found that in the DNA of any organism examined, the number of adenine bases was always equal to the number of thymine bases, and the number of guanine bases was equal to the number of cytosine bases. This information suggested that adenine and thymine, and guanine and cytosine, might link to each other and travel in pairs. The second "rule" that Chargaff found was that the amount of adenine- and thymine-bases, as compared with cytosine- and guanine- nucleotides, varied considerably from species to species.

Many researchers at that time felt that the six molecules (the four bases and the sugar and phosphate groups) in DNA were too few to fit the task. Proteins were already known to play a central role in the vital processes of all living organisms. To many scientists, DNA could not be the hereditary "master" molecule. How could DNA carry all instructions for life with only four kinds of variable subunits?

In this activity, you will be constructing a paper model of the DNA structure Watson and Crick proposed in 1953. As you piece the molecule together, keep in mind this question: How might this molecule encode all the information necessary for determining the biochemical activities and specific characteristics of all organisms?

MATERIALS NEEDED

For each group of four students:

- 1 large envelope containing copies of the following model pieces to cut out:
  - 10 of each of four bases
  - 20 phosphates
  - 20 sugars
- 4 small envelopes
- 2 paper strips (1 cm x 30 cm)
- masking tape (or drafting or other removable tape)
- white glue
- 4 scissors

PROCEDURE

1. Place your group's cutouts into four separate piles—one pile for the sugar molecules, one pile for the phosphate groups, combine the adenine and thymine bases into a third pile, and combine the cytosine and guanine bases into a fourth pile. ***NOTE:*** Each molecule has a right and left version.

2. STOP & THINK Why are you combining the adenines and thymines? The cytosines and guanines?

3. Remove five bases from pile three and five bases from pile four and scramble to make a random order. Place them in a line on the left side of your lab table.

4. Remove one sugar molecule from the sugar pile to attach to one of the bases. Glue the tab on the sugar (as a bond) to the lower corner of the base. (Look for the letter S at the corner of the base.) (See Figure 5.4.)

NOTE: When constructing the model, make sure the text on each molecule is facing up and can be read.

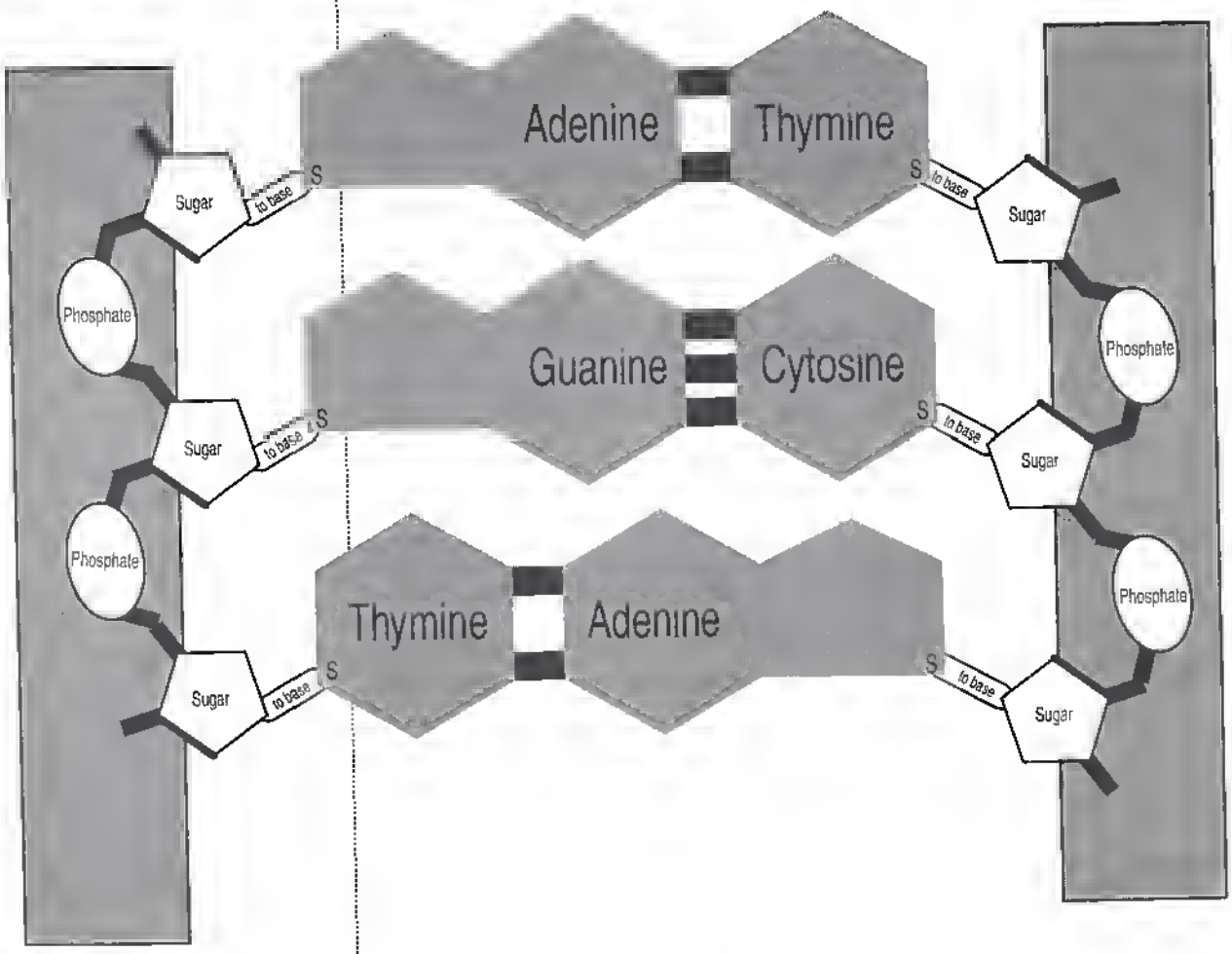


Figure 5.4
DNA model constructed with paper sides.

5. Remove one phosphate group from its pile to attach to the bonded sugar molecule. Glue the tabs.

6. Locate the appropriate matching (complementary) base from pile three or four to attach to the model. Attach the two bases by taping the "hydrogen bond" tabs together. (There are two bonds between Adenine and Thymine, and three bonds between Cytosine and Guanine).

7. STOP & THINK Read the Analysis questions that follow this procedure and discuss them with your group as you construct your model.
8. Repeat steps 3–6 for each of the bases lined up on the left side of your table, making ten complete sets of base pairs.
9. Complete the model by gluing the model to the two paper strips (see Figure 5.4).

ANALYSIS

As you and your group construct the model, discuss your responses to the following questions:

1. Describe the basic features of a DNA molecule. What information do the letter symbols give you?
2. What features of the DNA molecule remain constant in various organisms? What features differ?
3. How do the nucleotides connect to one another? How might the order or the placement of bases affect the code?

Write responses to the following questions in your notebook:

4. Write the sequence of bases for the DNA strand you constructed.
5. If 27% of the bases in a certain segment of DNA were adenine, what would be the percentages of thymine, cytosine, and guanine?
6. If DNA determines the characteristics of pneumococci, it seems possible that DNA could determine the traits of all living things. This means that DNA must be able to carry an enormous amount of information. How can a molecule composed of only four different kinds of subunits carry large amounts of diverse information?
7. How might DNA differ among different organisms; for example, how do you think mouse DNA or bacterial DNA differ from human DNA?

WRITING THE BOOK OF LIFE

READING

When Watson and Crick announced their model of the double helix in 1953, they described an extraordinary instruction "book" packed inside the nuclei of all our cells. Written in a language of few letters (four nucleotides), DNA contains all the information needed for the maintenance and perpetuation of life.

What roles were played by each of the component pieces—the sugars, the phosphates, and the bases—was the critical question Watson and Crick faced as they created and revised their DNA model. They knew they needed a pattern that could be written in thousands of variations. Yet a choice of only three pieces (sugar, phosphate, and base) did not initially seem to provide many options.

In the following excerpt, Crick (1954) describes his analysis of this elegant molecule:

Excerpted from

The Structure of the Hereditary Material

F.H.C. Crick, Scientific American, *October 1954, pages 54–61.*

...It is now known that DNA consists of a very long chain made up of alternate sugar and phosphate groups. The sugar is always the same sugar, known as deoxyribose. And it is always joined onto the phosphate in the same way, so that the long chain is perfectly regular, repeating the same phosphate-sugar sequence over and over again.

But while the phosphate-sugar chain is perfectly regular, the molecule as a whole is not, because each sugar has a "base" attached to it and the base is not always the same. Four different types of bases are commonly found: ...adenine and guanine... thymine and cytosine... So far as is known the order in which they follow one another along the chain is irregular, and probably varies from one piece of DNA to another. In fact, we suspect that the order of the bases is what confers specificity on a given DNA.

...we found that we could not arrange the bases any way we pleased; the four bases would fit into the structure only in certain pairs. In any pair, there must be one big one [the *purines* adenine and guanine] and one little one [the *pyrimidines* thymine and cytosine]. A pair of pyrimidines is too short to bridge the gap between the two chains, and a pair of purines is too big to fit into the space.

Adenine must always be paired with thymine, and guanine with cytosine; it is impossible to fit the bases together in any other combination in our model.... The model places no restriction, however, on the sequence of pairs along the structure. Any specified pair can follow any other. This is because a pair of bases is flat, and since in this model they are stacked roughly like a pile of coins, it does not matter which pair goes above which....

...the exciting thing about a model of this type is that it immediately suggests how the DNA might produce an exact copy of itself. The model consists of two parts, each of which is the complement of the other. Thus either chain may act as a sort of mold on which a complementary chain can be synthesized. The two chains of a DNA, let us say, unwind

and separate. Each begins to build a new complement onto itself. When the process is completed, there are two pairs of chains where we had only one. Moreover, because of the specific pairing of the bases the sequence of the pairs of bases will have been duplicated exactly; in other words, the mold has not only assembled the building blocks but has put them together in just the right order.

Let us imagine that we have a single helical chain of DNA, and that floating around it inside the cell is a supply of precursors of the four sorts of building blocks needed to make a new chain...from time to time, a loose unit will attach itself by its base to one of the bases of the single DNA chain. Another loose unit may attach itself to an adjoining base on the chain. Now if one or both of the two newly attached units is not the correct mate for the one it has joined on the chain, the two newcomers will be unable to link together, because they are not the right distance apart. One or both will soon drift away, to be replaced by other units. When, however, two adjacent newcomers are the correct partners for their opposite numbers on the chain, they will be in just the right position to be linked together and begin to form a new chain. Thus only the unit with the proper base will gain a permanent hold at any given position, and eventually the right partners will fill in the vacancies all along the forming chain. While this is going on, the other single chain of the original pair also will be forming a new chain complementary to itself.

...We suspect that the sequence of the bases acts as a kind of genetic code. Such an arrangement can carry an enormous amount of information. If we imagine that the pairs of bases correspond to the dots and dashes of the Morse code, there is enough DNA in a single cell of the human body to encode about 1,000 large textbooks...

The following figures illustrate several important ideas about the structure of DNA that Crick suggested in his article.

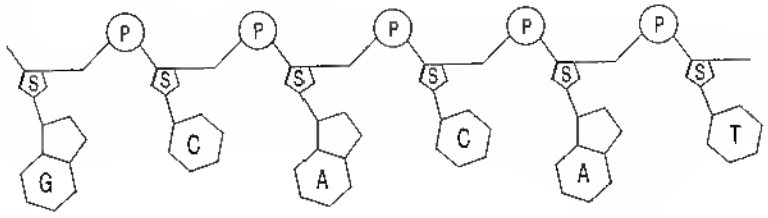
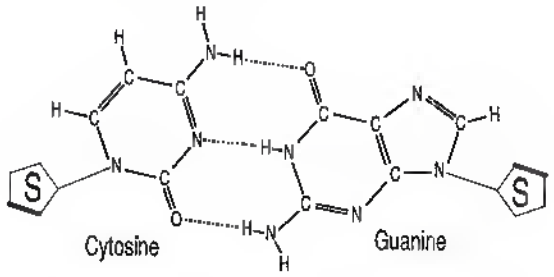


Figure 5.5
Crick's description of the DNA chain sounded much like a long chain made of links. This chain was formed by the sugar-phosphate backbone. From each of these links, bases were suspended. Each link with its base constituted a nucleotide subunit.



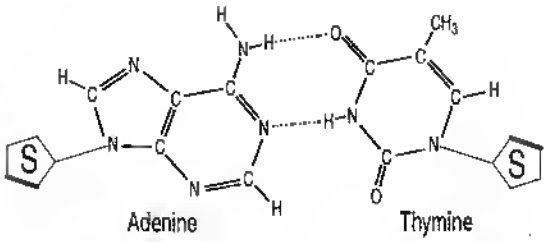


Figure 5.6
The relationship between the purines (adenine and guanine) and the pyrimidines (thymine and cytosine). Adenine always pairs with thymine; guanine always pairs with cytosine.

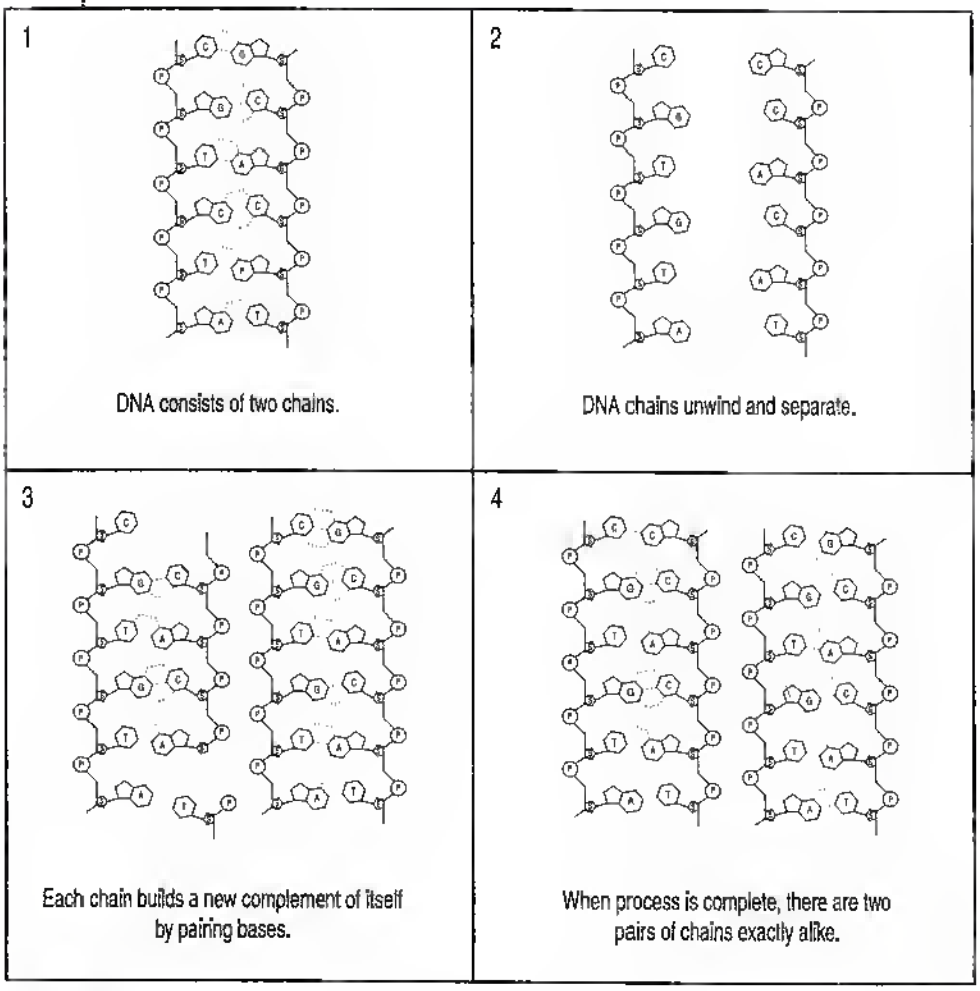


Figure 5.7
The model proposed by Watson and Crick suggests how DNA might produce an exact copy of itself.

Although Watson and Crick's model provided a giant leap in our understanding, a big question remained: How can a set of characters embedded in DNA actually determine what our bodies do? What could something like AGTCAT mean?

DNA as a Coded Plan

ACTIVITY

INTRODUCTION You began this learning experience with the questions: For what functions does your DNA plan? How might a DNA plan work?

When Watson and Crick published their model, they suggested that the sequence of the bases in DNA might act as a code. Although they were not sure at that time what DNA coded for, they thought it was intriguing that the structures of DNA and proteins were based on the same general plan. This plan included a regular, repeating backbone. The plan's variation came from the sequence of the bases of the nucleotides or the sidegroups of the amino acids.

With this new knowledge, protein and DNA researchers thought back to Griffith's transformation experiment. The protein researchers had argued that making a polysaccharide coat required enzymes to put the right building blocks together in the right arrangement. They believed that nothing in the cell could be built without the enzymes directing and facilitating the construction work. If a polysaccharide coat were built, proteins must be involved. The DNA researchers stood behind Avery's evidence that DNA was the transforming material.

When DNA and proteins were found to have such similar chemical arrangements, these two fields of research came together. Watson and Crick suggested that the four bases of the DNA might code for the 20 amino acids that make up the proteins of cells. In this light, the change in characteristics of the pneumococci did require the *work* of proteins. But it was the *plan* of the DNA that determined the protein would be made. The plan carried the information that directed which protein would be produced. That protein set to work to make the polysaccharide coat.

How exactly could this happen? How do the symbols of DNA contain the information for proteins? Crick suggested that the base symbols of DNA could be analogous to the dots and dashes of the Morse code. The Morse code uses only two symbols to represent all 26 letters, ten numbers, and a few punctuation marks. Placed in combinations of one to six symbols long for each letter or number, a set of symbols can make words and phrases. In turn, an infinite number of messages can be created.

A	•—	N	—•	1	•————
B	—•••	O	———	2	••———
C	—•—•	P	•——••	3	•••——
D	—••	Q	——•—	4	••••—
E	•	R	•—•	5	•••••
F	••—•	S	•••	6	—••••
G	——•	T	—	7	——•••
H	••••	U	••—	8	———••
I	••	V	•••—	9	————•
J	•———	W	•——	0	—————
K	—•—	X	—••—	.	•—•—•—
L	•—••	Y	—•——	,	——••——
M	——	Z	——••	?	••——••

TASK

Write responses to the following in your notebook:

1. Try writing your name in code, using the symbol system Morse set up.
2. Working in pairs, write a short sentence to your partner. When you are finished, swap sentences and try to decode your partner's message.
3. What similarities are there between Morse code and DNA? How might this apply to the way DNA and proteins work? In a short essay, explain what you know so far about the molecular languages of DNA and proteins. The following questions might help you to get started:
   a. Describe the makeup of these languages.
   b. How does one "speak" and make sense in each of these languages?
   c. How might the DNA alphabet be translated into the protein alphabet?
   d. How might DNA determine what a cell does?
4. Construct a concept map for DNA. Include the following terms: transforming factor, information, nucleotides, sugar, phosphate group, base pairs, building blocks, adenine, thymine, guanine, cytosine. Use additional terms as you need them.